

# Experimental summary: step-by-step towards new physics

**A J Schwartz**

Physics Department, University of Cincinnati, P.O. Box 210011, Cincinnati, Ohio 45221 USA

E-mail: alan.j.schwartz@uc.edu

**Abstract.** We summarize some highlights from experimental results presented at the XIIth International Conference on Beauty, Charm, and Hyperons in Hadronic Interactions, held at George Mason University June 12-18, 2016.

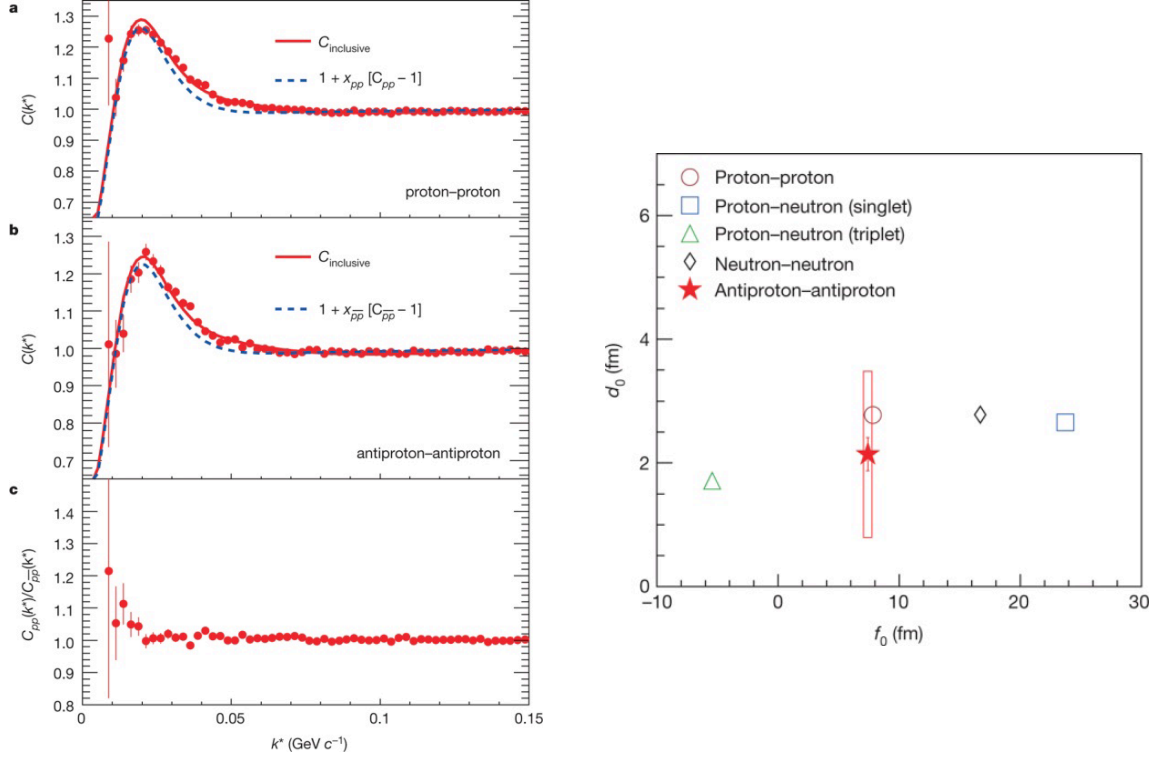
## 1. Introduction

This year's workshop featured about fifty experimental talks covering a wide variety of results in meson and baryon decays, heavy flavor and quarkonium production, heavy ion collisions, kaon physics, neutrino physics, and searches for new physics (NP). The presentations were organized as follows: heavy flavor production (Monday); heavy flavor decays (Tuesday); neutrino physics (Wednesday); mixing and  $CP$  violation (Thursday); spectroscopy (Thursday); and future experiments and facilities (Friday). Interspersed throughout the week were talks on searches for NP and theory talks. Experimental results were presented from ATLAS, ALICE, Belle, BaBar, BESIII, CDF, CMS, LHCb, PHENIX, and STAR. In this summary I discuss only a few highlights from among all these talks. For further details the reader is referred to the original presentations and these Proceedings.

## 2. Heavy flavor production

Numerous results were presented on the production of  $D$  and  $B$  mesons, charmonium and bottomonium mesons,  $W^\pm$  and  $Z^0$  vector bosons, and lighter pions and electrons, from LHC and RHIC experiments.

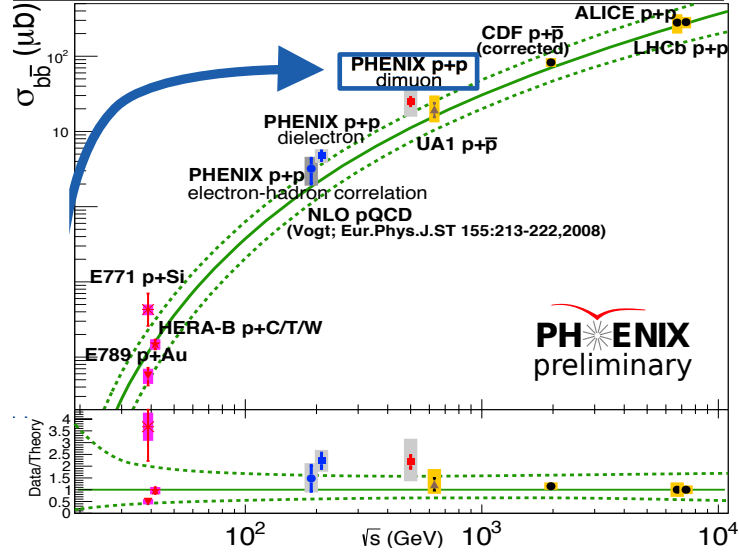
The STAR experiment (Zhang) presented measurements [1] of the correlation function  $C(k^*) \equiv A(k^*)/B(k^*)$ , where the variable  $k^*$  is half the relative momentum between two particles produced in a collision,  $A(k^*)$  is the distribution for a pair of particles in the same event, and  $B(k^*)$  is the distribution for two particles produced in *different* events. If there is a net attractive interaction between the particles,  $C(k^*)$  increases as  $k^*$  decreases; if there is a net repulsive interaction,  $C(k^*)$  decreases as  $k^*$  decreases; and if there is negligible interaction,  $C(k^*)$  is independent of  $k^*$  and equals unity. The STAR data corresponds to Au-Au collisions at  $\sqrt{s_{NN}} = 200$  GeV and is shown in Fig. 1(left). A strong attractive correlation is observed for both  $p$ - $p$  and  $\bar{p}$ - $\bar{p}$  distributions. Taking their ratio shows an equal attractive force over most of the  $k^*$  range. However, at the lowest  $k^*$  values the  $p$ - $p$  attractive force appears to be stronger. More data is needed to confirm this effect.



**Figure 1.** Data from Au-Au collisions at STAR. Left top: correlation function  $C(k^*)_{pp}$  for  $pp$  tracks; left middle: correlation function  $C(k^*)_{\bar{p}\bar{p}}$  for  $\bar{p}\bar{p}$  tracks; left bottom: ratio of  $C(k^*)_{pp}$  to  $C(k^*)_{\bar{p}\bar{p}}$ . The rise at low  $k^*$  for the top and middle plots indicates an attractive force. Right: values of the range  $d_0$  and scattering length  $f_0$  resulting from fitting the correlation functions  $C(k^*)_{pp}$  and  $C(k^*)_{\bar{p}\bar{p}}$ .

To measure a quantitative difference between  $p$ - $p$  and  $\bar{p}$ - $\bar{p}$  interactions and in this manner test  $CPT$ , STAR fits the  $p$ - $p$  and  $\bar{p}$ - $\bar{p}$  spectra for  $C(k^*)$  using the Lednický and Lyuboshitz model [2]. The fit yields two parameters: the effective range of the interaction  $d_0$ , and the scattering length  $f_0$ . The latter indicates whether the interaction corresponds to an attractive bound state ( $f_0 < 0$ ), an attractive but unbound state ( $f_0 > d_0$ ), or is repulsive ( $0 < f_0 < d_0$ ). The fit result is plotted in Fig. 1(right), which shows that  $d_0$  and also  $f_0$  are the same for  $p$ - $p$  and  $\bar{p}$ - $\bar{p}$  interactions, within errors. In both cases the range  $d_0$  is approximately 2.5 fm, and  $f_0$  corresponds to an attractive unbound state.

The LHCb experiment (Szumlak) presented measurements of differential cross sections for prompt and secondary  $J/\psi$  production,  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ , and  $\Upsilon(3S)$  production, and  $D$  and  $\Lambda_b$  production. All cross sections are measured as a function of  $p_T$  and rapidity  $y$  and correspond to  $pp$  collisions at  $\sqrt{s} = 7, 8$  TeV. From measurements of  $D^0$ ,  $D^{(*)+}$ , and  $D_s^+$  production, LHCb obtains a  $c\bar{c}$  total production cross section of  $(2940 \pm 3 \pm 180 \pm 160) \mu\text{b}$ , where the first error is statistical, the second is systematic, and the last error is due to the  $c \rightarrow D$  fragmentation model. From measurements of non-prompt  $J/\psi$  production, i.e., events in which the  $J/\psi$  candidate forms a secondary (rather than primary) vertex, LHCb calculates a  $b\bar{b}$  total production cross section of  $(515 \pm 2.0 \pm 53.0) \mu\text{b}$ . This value is plotted in Fig. 2 along with measurements of  $\sigma_{b\bar{b}}$  presented by PHENIX (Haseler). The latter results are from three independent analyses: one using same-sign  $\mu^\pm\mu^\pm$  pairs; one using opposite-sign  $e^+e^-$  pairs; and one using electron-hadron correlations. All  $\sigma_{b\bar{b}}$  measurements are in good agreement with next-to-leading-order pQCD [3]



**Figure 2.** Measurements of the  $b\bar{b}$  production cross section, and next-to-leading-order pQCD predictions [3].

over almost three orders of magnitude.

LHCb also measured the production of  $B_c^+$  mesons by reconstructing Cabibbo-favored  $B_c^+ \rightarrow J/\psi \pi^+$  decays [4]. The signal yield is normalized to the number of color-suppressed  $B^+ \rightarrow J/\psi K^+$  decays reconstructed, and the result is  $R \equiv [\sigma_{B_c^+} \cdot B(B_c^+ \rightarrow J/\psi \pi^+)]/[\sigma_{B^+} \cdot B(B^+ \rightarrow J/\psi K^+)] = (0.683 \pm 0.018 \pm 0.009)\%$ . This corresponds to the kinematic range  $2.5 < y < 4.5$  and  $4 < p_T < 20$  GeV/c.

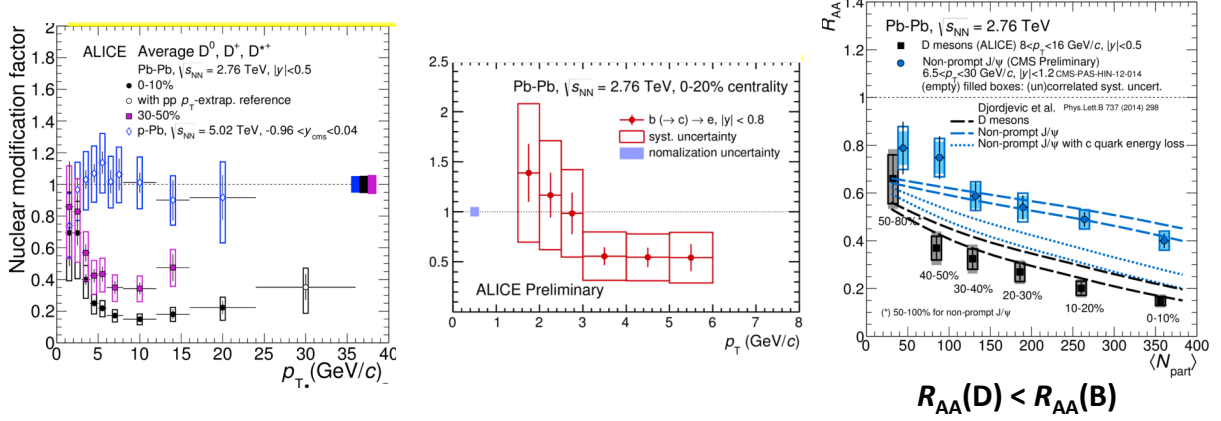
The ALICE experiment (De) presented results for meson production in proton-nucleus and nucleus-nucleus collisions. The energy density of such collisions corresponds to the environment of a quark-gluon plasma (QGP), and partons produced in collisions interact with the QGP when escaping and subsequently lose energy. This parton energy loss is expected to decrease as the parton mass increases. The parameter quantifying parton interactions with the QGP is the “nuclear modification factor:”

$$R_{AA}(p_T) \equiv \frac{1}{N_{\text{coll}}} \frac{(dN_{AA}/dp_T)}{(dN_{pp}/dp_T)}, \quad (1)$$

where  $N_{\text{coll}}$  is the number of nucleons participating in the  $A$ - $A$  collision. The greater the interaction with the QGP and subsequent energy loss, the lower  $R_{AA}(p_T)$ ; this is referred to as “suppression.” The amount of suppression is found to increase with  $p_T$ .

Figure 3(left) shows  $R_{AA}$  plotted as a function of  $p_T$  for  $D^0$  and  $D^{(*)+}$  production as measured by ALICE. The highest points correspond to  $p$ -Pb collisions and show little suppression; presumably the incoming proton does not generate a sufficient QGP energy density. The other points plotted correspond to Pb-Pb collisions and show large suppression. Figure 3(middle) shows  $R_{AA}$  for electrons in ALICE that have a large impact parameter with respect to the primary interaction point, i.e., they originate from heavy flavor decays. This data also shows significant suppression. Figure 3(right) shows  $R_{AA}$  as measured by ALICE for  $D$  mesons along with  $R_{AA}$  as measured by CMS [5] for  $J/\psi$  mesons having a large impact parameter with respect to the primary interaction; these  $J/\psi$  decays originate from  $B$  decays. The plot shows that  $R_{AA}^D < R_{AA}^B$ , as expected due to  $m_b > m_c$ . This data is an important confirmation of this

relationship. Also superimposed on the plot are several theoretical predictions [6], which are consistent with the data.



**Figure 3.** Left:  $R_{AA}^D$  measured by ALICE for  $D^0$  and  $D^{(*)+}$  production in Pb-Pb and p-Pb collisions. Middle:  $R_{AA}^B$  measured by ALICE for high-impact-parameter electrons in Pb-Pb collisions. Right:  $R_{AA}^D$  measured by ALICE as compared to  $R_{AA}^B$  measured by CMS using non-prompt  $J/\psi$  decays [5], in Pb-Pb collisions. Also shown are theoretical predictions [6].

### 3. Heavy flavor decays

The BESIII experiment (Ke) presented new measurements of branching fractions for the  $\Lambda_c^+$  baryon decaying into a dozen hadronic final states; see Table 1. With the exception of  $B(\Lambda_c^+ \rightarrow pK^-\pi^+)$  [7], the BESIII results are the world's most precise and represent a significant improvement over previous results. BESIII also presented  $\Lambda_c^+$  semileptonic branching fractions:

$$\begin{aligned} B(\Lambda_c^+ \rightarrow \Lambda\mu^+\nu_\mu) &= (3.49 \pm 0.46 \pm 0.26)\% \\ B(\Lambda_c^+ \rightarrow \Lambda e^+\nu_e) &= (3.63 \pm 0.38 \pm 0.20)\% \\ B(\Lambda\mu^+\nu_\mu)/B(\Lambda e^+\nu_e) &= 0.96 \pm 0.16 \pm 0.04. \end{aligned}$$

The last result constitutes a test of lepton universality in  $\Lambda_c^+$  decays.

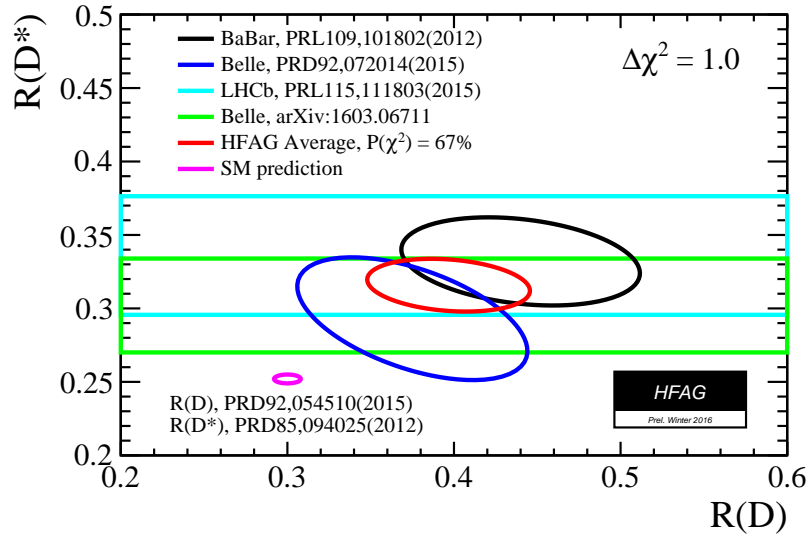
A higher precision test of lepton universality was presented by LHCb (Hamilton), which measured the ratio of branching fractions  $R_K \equiv B(B \rightarrow K\mu^+\mu^-)/B(B \rightarrow Ke^+e^-)$ . Within the Standard Model (SM), this ratio is within 0.1% of unity [8]. The measurement is challenging for LHCb due to the electrons. Photons reconstructed in the electromagnetic calorimeter that lie close to the candidate electron's trajectory are added to the electron's four-momentum to improve the resolution; as a consequence, the signal shape for the  $Ke^+e^-$  mass distribution must be treated separately for one, two, or three “recovered” photons. In addition, the background shape depends on whether the event was electron-triggered, kaon-triggered, or passed some other trigger criterion; thus the different trigger streams are fitted separately. The result is  $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$  for  $q^2 < (6 \text{ GeV})^2$ , which is  $2.6\sigma$  below unity. This measurement has significantly higher precision than similar measurements made by Belle [9] and BaBar [10].

The Belle experiment (King) presented a new result for the ratio  $R(D^*) \equiv B(B \rightarrow D^*\tau\nu_\tau)/B(B \rightarrow D^*\ell\nu)$  ( $\ell = e, \mu$ ) that uses “leptonic tagging,” i.e., events in which the opposite-side  $B$  is required to decay semileptonically, producing an electron or muon. This requirement significantly reduces backgrounds. The analysis obtains  $231 \pm 23$  signal ( $D^*\tau\nu$ ) decays and  $2800 \pm 57$  normalization ( $D^*\ell\nu$ ) decays; the result is  $R(D^*) = 0.302 \pm 0.030 \pm 0.011$ , which,

**Table 1.**  $\Lambda_c^+$  branching fractions to hadronic final states, as measured by BESIII.

Mode	BESIII	2014 PDG	Belle
$pK_S^0$	$1.52 \pm 0.08 \pm 0.03$	$1.15 \pm 0.30$	
$pK^- \pi^+$	$5.84 \pm 0.27 \pm 0.23$	$5.0 \pm 1.3$	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0 \pi^0$	$1.87 \pm 0.13 \pm 0.05$	$1.65 \pm 0.50$	
$pK_S^0 \pi^+ \pi^-$	$1.53 \pm 0.11 \pm 0.09$	$1.30 \pm 0.35$	
$pK^- \pi^+ \pi^0$	$4.53 \pm 0.23 \pm 0.30$	$3.4 \pm 1.0$	
$\Lambda \pi^+$	$1.24 \pm 0.07 \pm 0.03$	$1.07 \pm 0.28$	
$\Lambda \pi^+ \pi^0$	$7.01 \pm 0.37 \pm 0.19$	$3.6 \pm 1.3$	
$\Lambda \pi^+ \pi^- \pi^+$	$3.81 \pm 0.24 \pm 0.18$	$2.6 \pm 0.7$	
$\Sigma^0 \pi^+$	$1.27 \pm 0.08 \pm 0.03$	$1.05 \pm 0.28$	
$\Sigma^+ \pi^0$	$1.18 \pm 0.10 \pm 0.03$	$1.00 \pm 0.34$	
$\Sigma^+ \pi^+ \pi^-$	$4.25 \pm 0.24 \pm 0.20$	$3.6 \pm 1.0$	
$\Sigma^+ \omega$	$1.56 \pm 0.20 \pm 0.07$	$2.7 \pm 1.0$	

like a previous measurement by Belle using a hadronic tagging method [11], and also an LHCb measurement [12] (Hamilton), is significantly higher than the SM prediction of 0.25 [13]. Such a difference was also seen for the ratio  $R(D) = B(B \rightarrow D\tau\nu_\tau)/B(B \rightarrow D\ell\nu)$ , i.e., the measured values were higher than the SM prediction. All measurements and the SM predictions are summarized in Fig. 4.



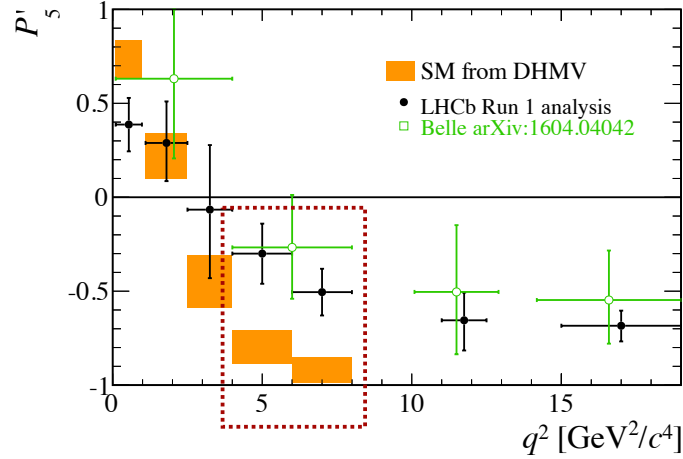
**Figure 4.** Measurements and theoretical predictions for  $R(D^*)$  and  $R(D)$ , as compiled by the Heavy Flavor Averaging Group [14].

Both Belle (King) and LHCb (Coutinho) presented results for the angular distribution of  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  decays. This distribution is parameterized as [15]:

$$\frac{d^4\Gamma}{dq^2 d\Omega} \propto \frac{3}{4}(1 - F_L) \sin^2 \theta_k + F_L \cos^2 \theta_k * \frac{1}{4}(1 - F_L) \sin^2 \theta_k \cos 2\theta_\ell - F_L \cos^2 \theta_k \cos 2\theta_\ell +$$

$$\begin{aligned}
& S_3 \sin^2 \theta_k \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_k \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_k \sin \theta_\ell \cos \phi + \\
& \frac{4}{3} A_{FB} \sin^2 \theta_k \cos \theta_\ell + S_7 \sin 2\theta_k \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_k \sin 2\theta_\ell \sin \phi + \\
& S_9 \sin^2 \theta_k \sin^2 \theta_\ell \sin 2\phi
\end{aligned} \tag{2}$$

where  $\theta_k$  is the helicity angle of the  $K^{0*} \rightarrow K^+ \pi^-$  decay,  $\theta_\ell$  is the helicity angle of the  $\mu^+ \mu^-$  system, and  $\phi$  is the azimuthal angle between the  $K^+ \pi^-$  plane and the  $\mu^+ \mu^-$  plane. There are eight underlying parameters, among which  $F_L$  is the longitudinal polarization of the final state, and  $A_{FB}$  is the forward-backward asymmetry of the  $\mu^+ \mu^-$  system. Calculations of these parameters have large theoretical uncertainties, but for the ratio  $P'_5 \equiv S_5 / \sqrt{F_L(1 - F_L)}$  the leading form factor uncertainties cancel [16]. Figure 5 shows measurements of  $P'_5$  from both Belle and LHCb as a function of  $q^2$ , which is the invariant mass squared of the  $\mu^+ \mu^-$  system. Superimposed on the data points are SM predictions [17]. There is good agreement between the measured values from the two experiments, but both experiments disagree with the SM prediction for  $4 \text{ GeV}^2/c^4 < q^2 < 8 \text{ GeV}^2/c^4$ . If these differences were statistical fluctuations, it is notable that both experiments observe fluctuations in the same direction for the same  $q^2$  bins. More data from LHCb and the future Belle II experiment is needed to better understand this difference.



**Figure 5.** Measurements and theoretical predictions [17] for the parameter  $P'_5$  measured in  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  decays.

#### 4. Mixing and $CP$ violation

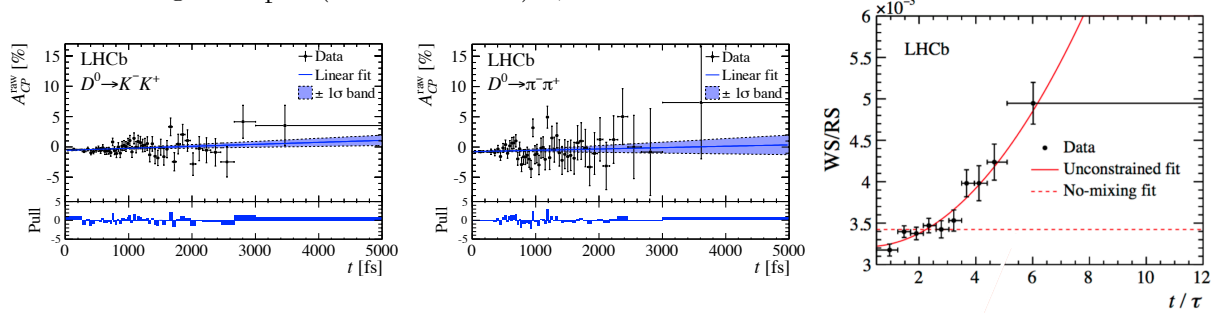
The LHCb experiment (Carbone) presented three measurements of  $D^0$ - $\bar{D}^0$  mixing and  $CP$  violation: measurements of  $A_\Gamma$  and  $A_{CP}$  in  $D^0 \rightarrow K^+ K^- / \pi^+ \pi^-$  decays, and a measurement of mixing in doubly Cabibbo-suppressed  $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$  decays.

The parameter  $A_\Gamma$  is defined as the asymmetry in lifetimes between  $D^0$  and  $\bar{D}^0$  decays:  $A_\Gamma = (\tau_{\bar{D}^0} - \tau_{D^0}) / (\tau_{\bar{D}^0} + \tau_{D^0})$ . One way to determine  $A_\Gamma$  is by fitting the decay time distribution of the  $CP$  asymmetry  $A_{CP}$  for decays to a self-conjugate final state  $f$ :

$$A_{CP}(t) = \frac{dN(D^0 \rightarrow f)/dt - dN(\bar{D}^0 \rightarrow f)/dt}{dN(D^0 \rightarrow f)/dt + dN(\bar{D}^0 \rightarrow f)/dt} \approx A_{CP}^{\text{dir}} - A_\Gamma \frac{t}{\tau}. \tag{3}$$

LHCb performs this measurement for  $D^0 \rightarrow K^+ K^-$  and  $D^0 \rightarrow \pi^+ \pi^-$  decays. The flavor of the decaying  $D^0$  or  $\bar{D}^0$  is identified by reconstructing  $D^{*+} \rightarrow D^0 \pi^+$  decays. The resulting

$A_{CP}$  distributions are shown in Fig. 6. Performing a simultaneous fit to the  $K^+K^-$  and  $\pi^+\pi^-$  distributions gives  $A_{CP} = (-0.125 \pm 0.073)\%$ , which is the world's most precise measurement.



**Figure 6.** LHCb measurements of the  $CP$  asymmetry in  $D^0 \rightarrow K^+K^-$  decays (left); the  $CP$  asymmetry in  $D^0 \rightarrow \pi^+\pi^-$  decays (middle); and the decay time distribution of  $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$  decays (right).

Using time-integrated (rather than time-dependent) samples of  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$  decays, LHCb measures  $CP$ -violating parameters  $a_{CP}^{\text{ind}}$  and  $\Delta a_{CP}^{\text{dir}} = a_{CP}^{\text{dir}}(K^+K^-) - a_{CP}^{\text{dir}}(\pi^+\pi^-)$ . For the analysis presented here the flavor of the  $D^0$  is determined by requiring that the  $D^0$  originate from semileptonic  $\bar{B}^0 \rightarrow D^0\mu^-\nu_\mu$  decays; the charge of the accompanying  $\mu^\pm$  then identifies the charm meson as  $D^0$  or  $\bar{D}^0$ . The results are  $a_{CP}^{\text{ind}} = (0.058 \pm 0.044)\%$  and  $\Delta a_{CP}^{\text{dir}} = (-0.061 \pm 0.076)\%$ , which are both consistent with no  $CP$  violation.

Finally, LHCb fits the decay time distribution of  $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$  decays to search for mixing in this doubly Cabibbo-suppressed decay mode. The decay time distribution, normalized to that for the Cabibbo-favored decay  $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ , is given by

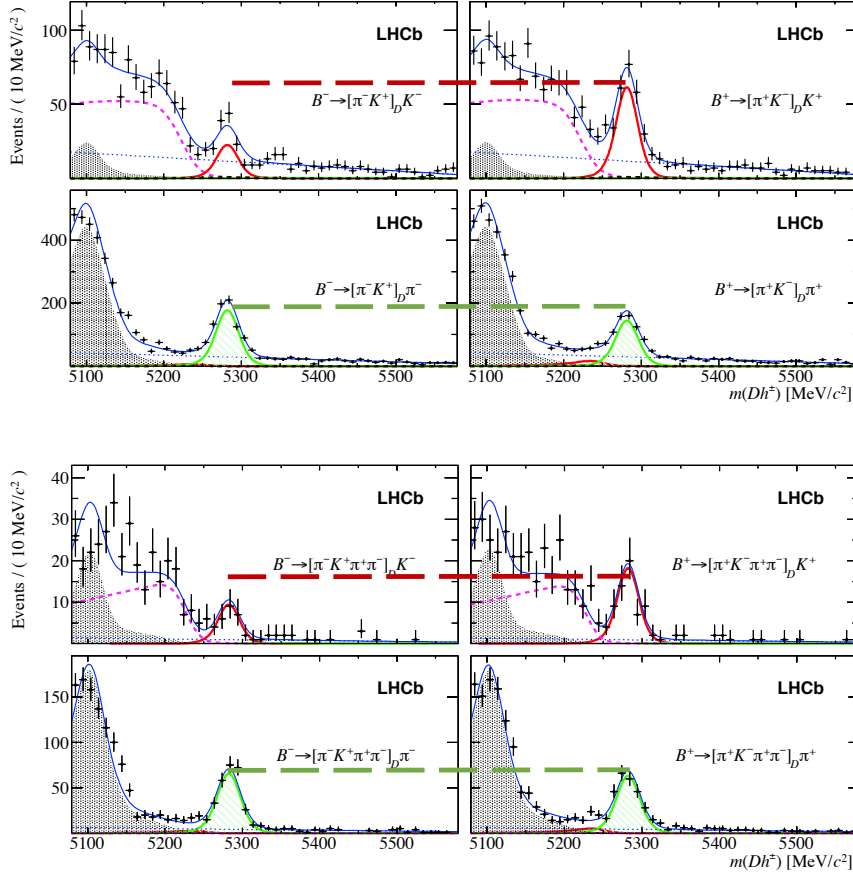
$$\frac{dN}{dt} \approx R_{K3\pi}^2 - \kappa^{K3\pi} \cdot R_{K3\pi} \cdot y'_{K3\pi} \cdot \left(\frac{t}{\tau}\right) + \frac{x^2 + y^2}{4} \cdot \left(\frac{t}{\tau}\right)^2 \quad (4)$$

where  $R_{K3\pi}^2$  is the ratio of the  $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$  amplitude squared integrated over phase space to the  $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$  amplitude squared integrated over phase space;  $\kappa^{K3\pi}$  is the coherence factor for  $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$  decays; and  $y'_{K3\pi} = y \cos \delta_{K3\pi} - x \sin \delta_{K3\pi}$ , where  $\delta_{K3\pi}$  is the average strong phase difference between the  $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$  and  $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$  amplitudes. The decay time distribution is shown in Fig. 6(right). Fitting this distribution to Eq. (4) gives  $(x^2 + y^2)/4 = (4.8 \pm 1.8) \times 10^{-5}$ , where the error includes systematic uncertainties. Due to a large correlation between the fitted terms  $\kappa^{K3\pi} y'_{K3\pi}$  and  $(x^2 + y^2)/4$ , the no-mixing hypothesis  $x = y = y'_{K3\pi} = 0$  is rejected with a relatively high significance:  $8.2\sigma$ .

LHCb (Whitehead) presented three measurements of the CKM phase  $\phi_3$  (or  $\gamma$ ). The first measurement is based on the Atwood-Dunietz-Soni method [18], in which one compares the rate for  $B^+ \rightarrow (D^0, \bar{D}^0)K^+, (D^0, \bar{D}^0) \rightarrow K^-\pi^+$  with that for the charge-conjugate decay  $B^- \rightarrow (D^0, \bar{D}^0)K^-, (D^0, \bar{D}^0) \rightarrow K^+\pi^-$ . These decays proceed through the interference of two amplitudes: a Cabibbo-favored  $B$  decay followed by a doubly Cabibbo-suppressed  $D$  decay, and a Cabibbo-suppressed  $B$  decay followed by a Cabibbo-favored  $D$  decay. The phase difference between the overall  $B^+$  and  $B^-$  decay amplitudes is  $2\phi_3$ , which results in a difference in decay rates. Previous measurements by Belle [19] and BaBar [20] had relatively low statistics. The LHCb data is shown in Fig. 7(top). Systematic uncertainties are determined by repeating the measurement with control samples of  $B^+ \rightarrow (D^0, \bar{D}^0)_{[K^-\pi^+]} \pi^+$  and  $B^- \rightarrow (D^0, \bar{D}^0)_{[K^+\pi^-]} \pi^-$  decays, which should exhibit no difference in decay rates. A total signal yield of  $553 \pm 54$  events is obtained, and a  $CP$  asymmetry is clearly visible; the statistical significance of the asymmetry is almost  $8\sigma$ . LHCb subsequently applied this method to four-body  $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$  decays and observed a similar  $CP$  asymmetry; see Fig. 7(bottom). However, the statistics is lower ( $159 \pm 17$



events) and the difference seen is not statistically significant. More data should establish a  $CP$  asymmetry in this mode also.



**Figure 7.** LHCb measurements of  $B^- \rightarrow (D^0, \bar{D}^0)K^-, (D^0, \bar{D}^0) \rightarrow K^+\pi^-$  decays (top left) and  $B^+ \rightarrow (D^0, \bar{D}^0)K^+, (D^0, \bar{D}^0) \rightarrow K^-\pi^+$  decays (top right). A clear  $CP$  asymmetry is seen. The control samples  $B^\mp \rightarrow D^0\pi^\mp$  are also shown. LHCb measurements of  $B^- \rightarrow (D^0, \bar{D}^0)K^-, (D^0, \bar{D}^0) \rightarrow K^+\pi^-\pi^+\pi^-$  decays (bottom left) and  $B^+ \rightarrow (D^0, \bar{D}^0)K^+, (D^0, \bar{D}^0) \rightarrow K^-\pi^+\pi^+\pi^-$  decays (bottom right). A clear  $CP$  asymmetry is also seen, although the statistics are low. The control samples  $B^\mp \rightarrow D^0\pi^\mp$  are also shown.

The ATLAS experiment (Barton) measured the  $B^0\text{-}\bar{B}^0$  mixing parameter  $\Delta\Gamma_d/\Gamma_d$ , where  $\Delta\Gamma_d$  is the difference in decay widths between the two mass eigenstates, and  $\Gamma_d$  is the mean decay width. For this measurement ATLAS reconstructs  $B^0 \rightarrow J/\psi K_S^0$  decays and fits the decay time distribution. This distribution contains four terms:

$$\frac{dN}{dt} \propto e^{-\Gamma t} \left[ \cosh \frac{\Delta\Gamma t}{2} + A_P A_{CP}^{\text{dir}} \cos(\Delta M t) + A_{\Delta\Gamma} \sinh \frac{\Delta\Gamma t}{2} + A_P A_{CP}^{\text{indir}} \sin(\Delta M t) \right] \quad (5)$$

where  $A_P$  is the production asymmetry between  $B^0$  and  $\bar{B}^0$  mesons. This parameter is measured by fitting the decay time distribution of flavor-specific  $B^0 \rightarrow J/\psi K^{*0}, K^{*0} \rightarrow K^+\pi^-$  decays, which should be purely exponential. The result is  $A_P = (0.25 \pm 0.48 \pm 0.05)\%$ . Inserting this into Eq. (5) along with the theoretical values  $A_{CP}^{\text{dir}} = 0$ ,  $A_{\Delta\Gamma} = \cos(2\phi_1)$ , and  $A_{CP}^{\text{mix}} = -\sin(2\phi_1)$ , ATLAS obtains  $\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1 \pm 0.9)\%$ . This result is (surprisingly) more precise than measurements made at the  $B$  factories and at LHCb, eclipsing the world's previous best



**Table 2.** Fitted parameters of exotic states used by LHCb to fit the  $M(J/\psi \phi)$  invariant mass distribution of  $B^+ \rightarrow J/\psi \phi K^+$  decays.

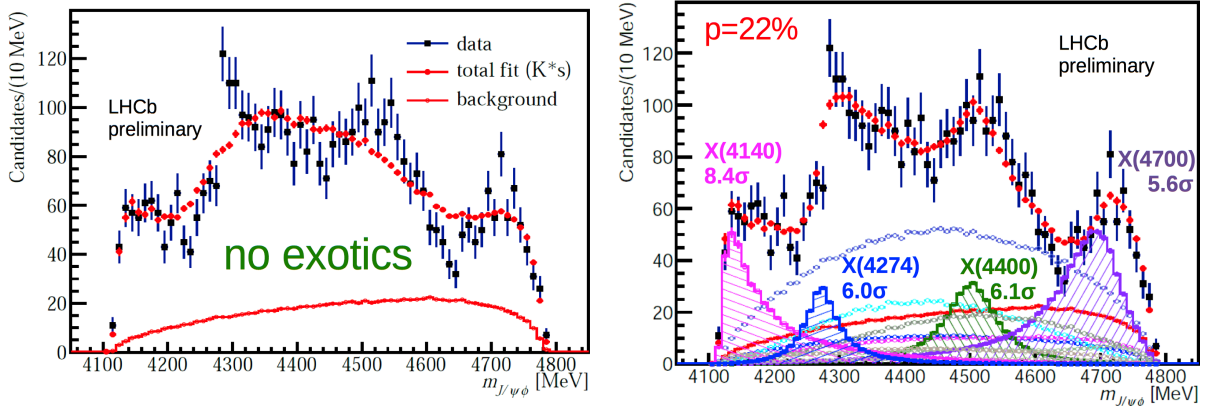
State	$J^{PC}$	significance	Mass	Width	Fit fraction
X(4140)	$1^{++}$	8.4	$4165 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$13.0 \pm 3.2^{+4.8}_{-2.0}$
X(4274)	$1^{++}$	6.0	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$7.1 \pm 2.5^{+3.5}_{-2.4}$
X(4500)	$0^{++}$	6.1	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$6.6 \pm 2.4^{+2.5}_{-2.3}$
X(4700)	$0^{++}$	6.1	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$12 \pm 5^{+9}_{-5}$

measurement of  $(1.7 \pm 1.8 \pm 1.1)\%$  (from Belle [21]). It is consistent with the SM prediction of  $(0.042 \pm 0.008)\%$  [22].

## 5. Spectroscopy

There were numerous talks on spectroscopy; here we discuss two recent results.

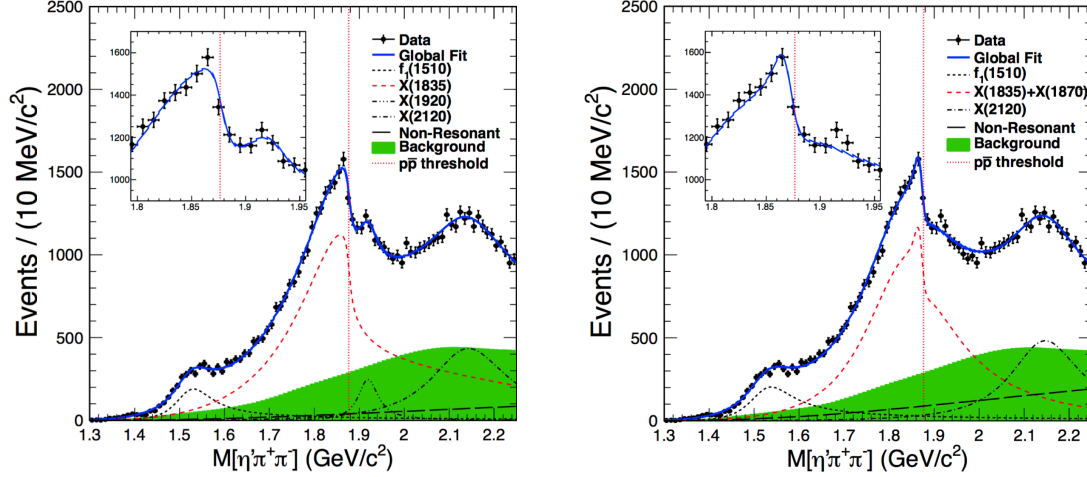
The LHCb experiment (Dey) reconstructed a large sample of  $B^+ \rightarrow J/\psi \phi K^+$  decays and studied the  $J/\psi$ - $\phi$  invariant mass distribution for unusual structure. This distribution is shown in Fig. 8(left) and exhibits four prominent peaks corresponding to the known states X(4140), X(4274), X(4500), and X(4700). Aside from these states no additional structure is apparent. Fitting the  $M(J/\psi \phi)$  distribution with these states plus background gives a satisfactory goodness-of-fit: the  $p$ -value is 0.22. The fit projection is shown in Fig. 8(right), and the fit results are listed in Table 2.



**Figure 8.** LHCb sample of  $B^+ \rightarrow J/\psi \phi K^+$  decays. The  $M(J/\psi \phi)$  invariant mass distribution is fitted without (left) and with (right) states X(4140), X(4274), X(4500), and X(4700).

The BESIII experiment (Pelizaus) reconstructed an especially large sample of  $J/\psi \rightarrow \eta' \pi^+ \pi^- \gamma$  decays with the goal of identifying intermediate  $J/\psi \rightarrow X(1835) \gamma$  decays followed by  $X(1835) \rightarrow \eta' \pi^+ \pi^-$ . The  $\eta'$  is reconstructed in both  $\eta' \rightarrow \rho^0 \gamma$  and  $\eta' \rightarrow \eta \pi^+ \pi^-$  modes, where  $\eta \rightarrow \gamma \gamma$ . The resulting  $M(\eta' \pi^+ \pi^-)$  invariant mass distribution shows a clear peak near  $M \approx 1835 \text{ MeV}/c^2$ , as expected, but it also shows a sharp drop at the  $p\bar{p}$  threshold, which was unexpected. The observed lineshape including this drop is subsequently modeled in two ways: with a broad X(1835) state and a narrow X(1920) state (the latter being just above  $p\bar{p}$  threshold); and with

a broad  $X(1835)$  state and a narrow  $X(1870)$  state (the latter being just below  $p\bar{p}$  threshold). Both parameterizations give satisfactory fits, which are shown in Fig. 9.



**Figure 9.** BESIII sample of  $J/\psi \rightarrow \eta' \pi^+ \pi^- \gamma$  decays. Left: fit result with a broad  $X(1835)$  state and a narrow  $X(1920)$  state. Right: fit result with a broad  $X(1835)$  state and a narrow  $X(1870)$  state. Both fits are satisfactory.

## Acknowledgments

The authors thank the BEACH 2016 organizers for a well-run workshop and excellent hospitality. This research is supported by the U.S. Department of Energy.

## References

- [1] Adamczyk L *et al* (STAR Collaboration) 2015 *Nature* **527** 345348
- [2] Lednický R, Lyuboshitz V L and Lyuboshitz V V 2004 *Phys. Part. Nucl.* **35** S50-S53  
Lednický R and Lyuboshitz V 2001 *Phys. Lett. B* **508** 146-154
- [3] Vogt R 2008 *Eur. Phys. J. ST* **155** 213-222
- [4] Charge-conjugate modes are implicitly included unless noted otherwise
- [5] CMS Collaboration 2012 *Preprint* CMS-PAS-HIN-12-014
- [6] Djordjevic M, Djordjevic M and Blagojevic B 2014 *Phys. Lett. B* **737** 298-302
- [7] Zupanc A *et al* (Belle Collaboration) 2014 *Phys. Rev. Lett.* **113** 042002
- [8] Bobeth C, Hiller G and Piranishvili G 2007 *J. High Energy Phys.* JHEP12(2007)040  
Bouchard C, Lepage G P, Monahan C, Na H and Shigemitsu J 2013 *Phys. Rev. Lett.* **111** 162002
- [9] Wei J-T *et al* (Belle Collaboration) 2009 *Phys. Rev. Lett.* **103** 171801
- [10] Lees J P *et al* (BaBar Collaboration) 2012 *Phys. Rev. D* **86** 032012
- [11] Huschle M *et al* (Belle Collaboration) 2015 *Phys. Rev. D* **92** 072014
- [12] Aaij R *et al* (LHCb Collaboration) 2015 *Phys. Rev. Lett.* **115** 111803  
Erratum 2015 *Phys. Rev. Lett.* **115** 159901
- [13] Fajfer S, Kamenik J F and Niandi I 2012 *Phys. Rev. D* **85** 094025
- [14] Amhis Y *et al* (Heavy Flavor Averaging Group) 2014 *Preprint* arXiv:1412.7515 and online update at [www.slac.stanford.edu/xorg/hfag/](http://www.slac.stanford.edu/xorg/hfag/)
- [15] Aaij R *et al* (LHCb Collaboration) 2016 *J. High Energy Phys.* JHEP02(2016)104
- [16] Descotes-Genon S, Matias J, Ramon M and Virto J 2013 *J. High Energy Phys.* JHEP01(2013)048
- [17] Descotes-Genon S, Hofer L, Matias J and Virto J 2014 *J. High Energy Phys.* JHEP12(2014)125
- [18] Atwood D, Dunietz I and Soni A 1997 *Phys. Rev. Lett.* **78** 3257-3260
- [19] Horii Y *et al* (Belle Collaboration) 2011 *Phys. Rev. Lett.* **106** 231803
- [20] del Amo Sanchez P *et al* (BaBar Collaboration) 2010 *Phys. Rev. D* **82** 072006
- [21] Higuchi T *et al* (Belle Collaboration) 2012 *Phys. Rev. D* **85** 071105
- [22] Bobeth C, Haisch U, Lenz A, Pecjak B and Tetlalmatzi-Xolocotzi G 2014 *J. High Energy Phys.* JHEP06(2014)040